



## Measurement of $D_s^\pm$ and $D^\pm$ Decays to Non-Strange States\*

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Using the data from Fermilab experiment E691, we have observed signals for the decays  $D_S^\pm$  and  $D^\pm \rightarrow \pi^- \pi^+ \pi^\pm$  and have analyzed these modes for the fraction due to  $\rho^0 \pi^\pm$  and  $f_0(975) \pi^\pm$ . In addition, we have searched for the decays  $D_S^\pm$  and  $D^\pm \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^\pm$ . Values or upper limits are reported for the relative branching fractions for all of the above decays.

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A notable feature of the charmed mesons is the difference in their lifetimes:<sup>1</sup> the  $D^+$  lifetime is more than twice that of the  $D^0$  or  $D_S^+$ . Among the possible explanations are that 1) non-spectator diagrams, not available in  $D^+$  decay, have amplitudes comparable to those of spectator diagrams for the  $D^0$  and  $D_S^+$ , and 2) the  $D^+$  decay rate is suppressed by destructive interference of spectator diagrams, which cannot occur for the  $D^0$  and  $D_S^+$ . A consequence of explanation 1) might be an observable rate for the decay  $D_S^\pm \rightarrow \pi^- \pi^+ \pi^\pm$ , which could occur via the Cabibbo allowed annihilation sub-process  $c\bar{s} \rightarrow W^+ \rightarrow u\bar{d}$ , but is unlikely to occur via the spectator diagram. The explanation 2) suggests that the decay rate for  $D^\pm \rightarrow \pi^- \pi^+ \pi^\pm$  could be suppressed relative to that for  $D^\pm \rightarrow K^- K^+ \pi^\pm$  since interference is possible for the former decay but not the latter.

In this paper, we report the first observation of the decay  $D_S^\pm \rightarrow \pi^- \pi^+ \pi^\pm$  and the most accurate measurement to date of the decay  $D^\pm \rightarrow \pi^- \pi^+ \pi^\pm$ . For both of these decays, we determine the fraction of  $\pi^- \pi^+ \pi^\pm$  decays due to the quasi-2-body states  $\rho^0 \pi^\pm$  and  $f_0 \pi^\pm$ . We also report on the results of a search for  $D_S^\pm$  and  $D^\pm \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^\pm$ . Henceforth, each decay mode will stand implicitly for the charge-conjugate mode as well.

This study utilizes the sample of  $10^8$  events recorded from Fermilab experiment 691,<sup>1</sup> in which high energy photon-beryllium interactions were detected with a silicon vertex hodoscope, magnetic spectrometer, and multi-cell threshold Cerenkov counters. To reduce the computing load for detailed event analysis, a data subset was extracted by performing a general vertex reconstruction, producing a list of possible vertices with  $\chi^2/\text{DOF} < 3$ , and then selecting events with secondary vertices. Events with a 3-prong charm decay candidate are required to have the following vertex properties: 1) there must be at least one downstream vertex that has three and only three tracks; 2) the secondary vertex does not share tracks with any vertex candidate upstream of it; 3) all three tracks go through both magnets; 4) the summed 3-momentum vector of the secondary tracks points back to the primary vertex with

an impact parameter less than  $80 \mu\text{m}$  and 5) the vertex separation,  $\Delta z$ , along the beam direction, must be greater than  $15 \sigma_{\Delta z}$ , where  $\sigma_{\Delta z}$  is the error in  $\Delta z$ . Finally, the tracks from the charm decay vertex are required to have Cerenkov counter pulse heights consistent with the  $\pi\pi\pi$  mass hypothesis.

A  $\pi^-\pi^+\pi^+$  mass plot, with the cuts described above, is shown in Figure 1. There are clear peaks for both the  $D^+$  and  $D_s^+$ . The peak at  $1.75 \text{ GeV}/c^2$  is due to the decays  $D^+ \rightarrow K^-\pi^+\pi^+$  which are misidentified as  $\pi^-\pi^+\pi^+$ . A maximum likelihood fit, shown in the figure, gives  $82.6 \pm 15.3$   $D^+$  decays and  $68.1 \pm 12.4$   $D_s^+$  decays. The fit is to Gaussian signals and a background shape that is the sum of a linear term and a Gaussian term for the false peak. The masses are fixed at  $1.869 \text{ GeV}/c^2$  for the  $D^+$  and  $1.968 \text{ GeV}/c^2$  for the  $D_s^+$  and the widths are fixed on the basis of Monte Carlo analysis, as are the parameters for the shape of the false peak.

To demonstrate the resonant structure of these decays, Dalitz plots are shown in Figure 2(a) for the mass range  $1.854$  to  $1.884 \text{ GeV}/c^2$ , encompassing the  $D^+$ , and in 2(b) for the range  $1.953$  to  $1.983 \text{ GeV}/c^2$ , encompassing the  $D_s^+$ . In these Dalitz plots, the  $\pi^-\pi^+$  combination with the higher invariant mass is plotted on the vertical axis. To determine if any  $\pi^-\pi^+$  resonances are present, projections of a given Dalitz plot are made onto both the vertical and horizontal axes and then summed to give a histogram containing two entries of  $\pi^-\pi^+$  invariant mass for each  $\pi^-\pi^+\pi^+$  event. These histograms are shown in Figure 3. There is evidence for  $D^+ \rightarrow \rho^0\pi^+$  in histogram 3(a) and for  $D_s^+ \rightarrow f_0(975)\pi^+$  in 3(b). The  $f_0(975)$ , formerly called the  $S^*$ , is an  $s\bar{s}$  resonance below  $K\bar{K}$  threshold which decays primarily to pions.

To determine the fraction of  $\pi^-\pi^+\pi^+$  decays due to  $\rho\pi^+$  or  $f_0\pi^+$ , a maximum likelihood fit is made to the distribution of  $\pi^-\pi^+\pi^+$  decay candidates taking into account, for each

decay, the  $\pi^-\pi^+\pi^+$  invariant mass and the two  $\pi^-\pi^+$  invariant mass combinations. The  $\pi^-\pi^+\pi^+$  invariant mass is restricted to the range 1.820 to 1.920 GeV/c<sup>2</sup> for the  $D^+$  fit, and the range 1.920 to 2.020 GeV/c<sup>2</sup> is used for the  $D_s^+$  fit. The assumed probability density,  $p$ , is of the form,

$$p(\pi^-\pi_1^+\pi_2^+) = \sum_{i=1}^4 F_i(\pi^-\pi^+\pi^+) f_i(\pi^-\pi_1^+, \pi^-\pi_2^+) c_i N_i \quad (1)$$

where the terms,  $i$ , are due to 1) non-resonant (NR) 3-body decay, 2) quasi-2-body decay, 3)  $\pi^-\pi^+\pi^+$  combinatoric background, and 4) background from  $\rho^0 \rightarrow \pi^-\pi^+$  in combination with an unrelated  $\pi^+$ . The functions  $F_i$  give the dependence on the  $\pi^-\pi^+\pi^+$  invariant mass, previously discussed, and the functions  $f_i$  give the form of the distribution over the Dalitz plot. For the decay  $D^+ \rightarrow \rho^0 \pi^+$ ,  $f = |a_\rho(\pi^-\pi_1^+) + a_\rho(\pi^-\pi_2^+)|^2$ , where,

$$a_\rho(\pi^-\pi_1^+) = \frac{\Gamma_\rho/2}{m(\pi^-\pi_1^+) - m(\rho) + i\Gamma_\rho/2} \cos\theta_{\pi^-\pi_2^+}$$

Note that  $f$  is symmetric under exchange of the two identical  $\pi^+$  mesons as required to describe the interference between the  $\pi^-\pi_1^+$  and  $\pi^-\pi_2^+$  amplitudes. For the decay  $D_s^+ \rightarrow f^0 \pi^+$ ,  $f = |a_f(\pi^-\pi_1^+) + a_f(\pi^-\pi_2^+)|^2$ , where the amplitude  $a_f$  has the form<sup>2</sup> of a coupled channel Breit-Wigner resonance with parameters fixed from data<sup>2</sup> for  $\psi \rightarrow f_0 + X$ . The amplitude  $a_f$  does not depend on  $\cos(\theta)$  since the  $f_0$  has spin 0. The  $\pi^-\pi^+\pi^+$  combinatoric background was found to be uniformly distributed over the Dalitz plot. For the  $\rho^0 \pi^+$  background,  $f = |a(\pi^-\pi_1^+)|^2 + |a(\pi^-\pi_2^+)|^2$ , where  $a$  is the Breit-Wigner amplitude for the  $\rho$  with no dependence on  $\cos(\theta)$ . The constants  $c_i$  provide the normalization for the functions  $f_i$  in equation (1). Each  $c_i$  is the reciprocal of the integral of  $f_i$  over the Dalitz plot for a given  $\pi^-\pi^+\pi^+$  mass. The parameters  $N_i$  are determined from the fit and give the number of events of each type  $i$ . The fitting procedure described above gives  $N(D_s^+ \rightarrow f^0 \pi^+) = 22.4 \pm 7.3$  and  $N(D^+ \rightarrow \rho^0 \pi^+) = 19.1 \pm 11.3$ . The fits are superimposed on the projections of Dalitz plots in Figure 3.

When interference between the  $\rho^0\pi^+$  and s-wave  $\pi^-\pi^+\pi^+$  signal amplitudes was allowed in the fit, no significant change was found in the fitted number of these decays for either the  $D^+$  or the  $D_S^+$ . When terms were included in the fit to allow for  $D^+\rightarrow f_0\pi^+$  and  $D_S^+\rightarrow \rho^0\pi^+$ , no significant signals were found for these modes. For  $D_S^+\rightarrow \rho^0\pi^+$ , the fit gave  $-1.7\pm 7.7$  events.

To compute relative branching fractions for  $D_S^+$  and  $D^+$  decays, we chose to normalize to the most easily measured decay modes:  $D_S^+\rightarrow \phi\pi^+$  and  $D^+\rightarrow K^-\pi^+\pi^+$ . To obtain signals for these decays, we used tracking and vertex requirements identical to those used for the  $3\pi$  decays. Cerenkov cuts were chosen appropriately for  $D^+\rightarrow K^-\pi^+\pi^+$ , but no Cerenkov cuts were used for the decay  $D_S^+\rightarrow \phi\pi^+$ ,  $\phi\rightarrow K^-K^+$ . For the latter decay, the  $K^-K^+$  mass was required to be in the range 1.012 to 1.027 GeV/c<sup>2</sup>, and it was required that  $|\cos(\theta_{K\pi})| > .3$ . These cuts yielded signals of  $77.5\pm 9.4$   $D_S^+\rightarrow \phi\pi^+$  events and  $2214\pm 62$   $D^+\rightarrow K^-\pi^+\pi^+$  events. Mass plots for these decays, from the E691 data and with cuts similar to those used here, have been previously published.<sup>1</sup>

The relative branching ratios,  $B$ , of 3-body states reported in this paper are nearly independent of the properties of our apparatus because these ratios compare decays of identical particles to final states that differ only by the particle masses,  $m_\pi$  or  $m_K$ . A Monte Carlo simulation was used to determine that the ratios of acceptances,  $A$ , are:  $A(D_S^+\rightarrow \pi^-\pi^+\pi^+) / A(D_S^+\rightarrow K^-K^+\pi^+, K^-K^+ \text{ from } \phi) = 1.00\pm 0.10$ , and  $A(D^+\rightarrow \pi^-\pi^+\pi^+) / A(D^+\rightarrow K^-\pi^+\pi^+) = 1.06\pm 0.08$ . For both  $D_S^+$  and  $D^+\rightarrow \pi^-\pi^+\pi^+$ , the acceptance over the Dalitz plot was found to be uniform. Our results for relative branching ratios,  $B$ , are shown in Table 1.

There is no significant contribution to the decay  $D_S^+\rightarrow \pi^-\pi^+\pi^+$  from  $\rho^0\pi^+$ . Our upper limit for the decay  $D_S^+\rightarrow \rho^0\pi^+$  is nearly 3 times smaller than the existing limit.<sup>3</sup> To determine the rate for  $D_S^+\rightarrow \pi^-\pi^+\pi^+$  due to annihilation, we exclude the contribution from

the decay  $D_S^+ \rightarrow f_0 \pi^+$  which most likely originates from the  $s\bar{s}$  quark pair present after spectator diagram decay and not from annihilation. Thus, the non-zero rate for  $D_S^+ \rightarrow (\pi^- \pi^+ \pi^+)_{NR}$  (given in Table 1) is a measure of annihilation, and can be compared to the rate due to the spectator diagram decay  $D_S^+ \rightarrow K^- K^+ \pi^+$  by combining the results presented here with previously published data from this experiment.<sup>4</sup> We find  $B(D_S^+ \rightarrow \pi^- \pi^+ \pi^+)_{NR} / B(D_S^+ \rightarrow K^- K^+ \pi^+) = .14 \pm .04$ . Thus, the rate for  $D_S^+$  decay that can be attributed to annihilation is small compared to that due to the spectator diagram. This suggests that annihilation is not the dominant cause of the  $D_S^+/D^+$  lifetime difference.

It might be possible that the annihilation contribution to the total  $D_S^+$  decay rate is dominated by high multiplicity modes. To test this hypothesis, and to search for new decay modes, we performed an analysis for the decays  $D^+$  and  $D_S^+ \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^+$  using techniques similar to those described for  $D^+$  and  $D_S^+ \rightarrow \pi^- \pi^+ \pi^+$ . No signals for the  $5\pi$  modes were apparent. A maximum likelihood fit to the  $5\pi$  mass plot gave event estimates used to establish the 90% confidence level (c.l.) limits shown in Table 1.

Our result,  $B(D^+ \rightarrow \pi^- \pi^+ \pi^+) / B(D^+ \rightarrow K^- \pi^+ \pi^+) = .035 \pm .007 \pm .003$ , is consistent with the MARK III value<sup>5</sup>  $.042 \pm .016 \pm .010$ . Using the results given here and previous data from E691, we find,  $(B(D^+ \rightarrow \rho^0 \pi^+) / B(D^+ \rightarrow \phi \pi^+)) (PS(\phi \pi) / PS(\rho \pi)) = .10 \pm .06$ , and  $(B(D^+ \rightarrow \pi^- \pi^+ \pi^+)_{NR} / B(D^+ \rightarrow K^- K^+ \pi^+)_{NR}) (PS(KK\pi) / PS(\pi\pi\pi)) = .18 \pm .06$ , where PS is the phase space factor. Thus, decay modes in which destructive interference is possible are clearly suppressed relative to those without interference.

In conclusion, we have measured a non-zero decay rate for  $D_S^+ \rightarrow \pi^- \pi^+ \pi^+$  and have determined that the partial rate which can be attributed to annihilation does not have a large effect on the  $D_S^+/D^+$  lifetime difference. Our measurement of the decay rate for  $D^+ \rightarrow \pi^- \pi^+ \pi^+$  shows significant suppression relative to the rate for  $D^+ \rightarrow K^- K^+ \pi^+$ , an effect



which can be interpreted as evidence for the destructive interference of spectator diagrams.

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<sup>1</sup>J. R. Raab *et al.*, Phys. Rev. **D37** 2319 (1988).

<sup>2</sup>G. Gidal *et al.*, Phys. Lett. **107B** 153 (1981).

<sup>3</sup>H. Albrecht *et al.*, Phys. Lett. **195B** 102 (1987).

<sup>4</sup>J. C. Anjos *et al.*, Phys. Rev. Lett. **60** 10 (1988).

<sup>5</sup>R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **55** 150 (1985); R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56** 2140 (1986).

TABLE I. Relative branching ratios (B) for  $D_S^+$  and  $D^+ \rightarrow$  non-strange states. Errors are given in the form:  $\pm$ statistical  $\pm$ systematic.

Decay mode 1	Decay mode 2	B(decay mode1)/B(decay mode2)
$D_S^+ \rightarrow \pi^- \pi^+ \pi^+$	$D_S^+ \rightarrow \phi \pi^+$	$.44 \pm .10 \pm .04$
$D_S^+ \rightarrow (\pi^- \pi^+ \pi^+)_{NR}$	$D_S^+ \rightarrow \phi \pi^+$	$.29 \pm .09 \pm .03$
$D_S^+ \rightarrow \rho^0 \pi^+$	$D_S^+ \rightarrow \phi \pi^+$	$< .08$ (90% c.l.)
$D_S^+ \rightarrow f_0 \pi^+$	$D_S^+ \rightarrow \phi \pi^+$	$.28 \pm .10 \pm .03$
$D^+ \rightarrow \pi^- \pi^+ \pi^+$	$D^+ \rightarrow K^- \pi^+ \pi^+$	$.035 \pm .007 \pm .003$
$D^+ \rightarrow (\pi^- \pi^+ \pi^+)_{NR}$	$D^+ \rightarrow K^- \pi^+ \pi^+$	$.027 \pm .007 \pm .002$
$D^+ \rightarrow \rho^0 \pi^+$	$D^+ \rightarrow K^- \pi^+ \pi^+$	$.008 \pm .005 \pm .001$
$D_S^+ \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^+$	$D_S^+ \rightarrow \phi \pi^+$	$< 0.29$ (90% c.l.)
$D^+ \rightarrow \pi^- \pi^+ \pi^- \pi^+ \pi^+$	$D^+ \rightarrow K^- \pi^+ \pi^+$	$< 0.019$ (90% c.l.)

### Figure Captions

1. Histogram of  $\pi^- \pi^+ \pi^+$  mass combinations.
2. Dalitz plot of  $\pi^- \pi_1^+$  mass<sup>2</sup> versus  $\pi^- \pi_2^+$  mass<sup>2</sup> for (a) events with  $\pi^- \pi_1^+ \pi_2^+$  mass in the range 1.854 - 1.884 GeV/c<sup>2</sup>, (b) events with  $\pi^- \pi_1^+ \pi_2^+$  mass in the range 1.953 - 1.983 GeV/c<sup>2</sup>.
3. Sum of Dalitz plot projections onto  $\pi^- \pi_1^+$  mass<sup>2</sup> axis and  $\pi^- \pi_2^+$  mass<sup>2</sup> axis; (a) and (b) of this figure correspond to (a) and (b) of Figure 2.

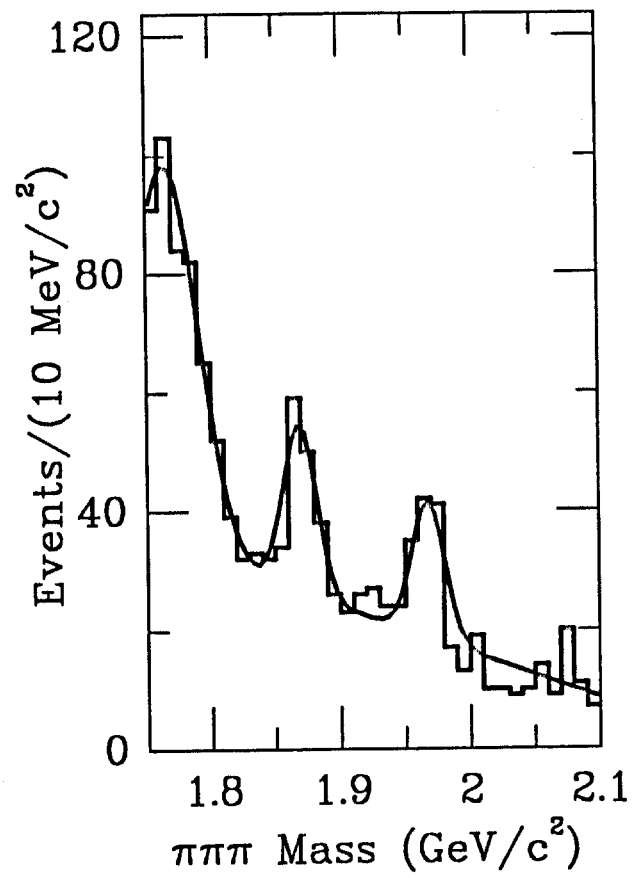


Figure 1

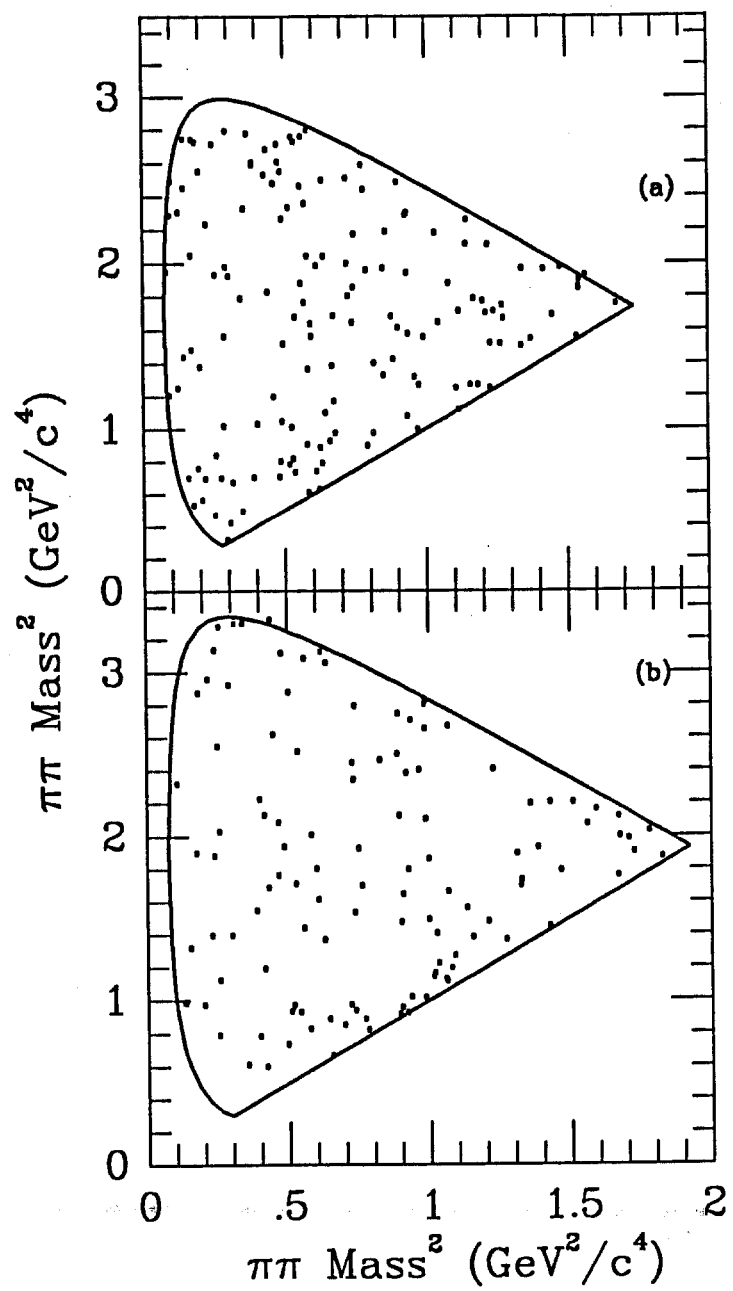


Figure 2

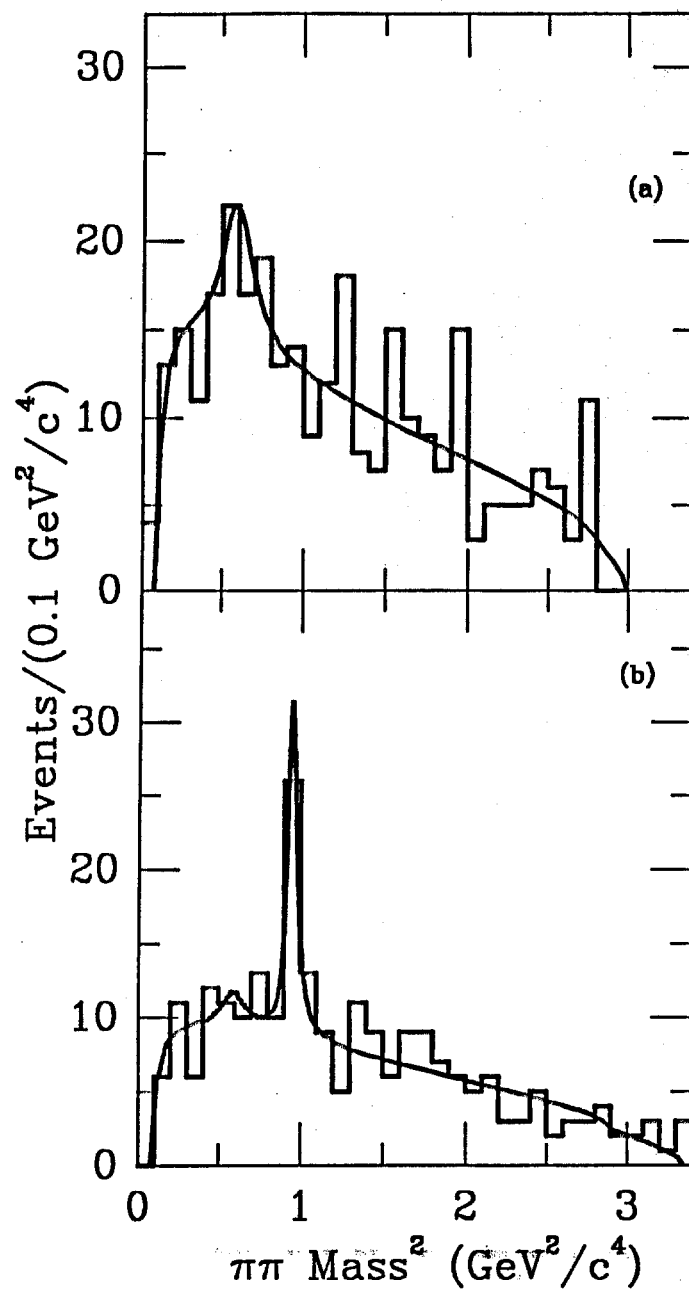


Figure 3